Table 10. Estimates of RBE of tritium beta particles for carcinogenesis endpoints[a]

Effect	Radiation and conditions	RBE	Reference
Mammary tumors in S-D rats	HTO and chronic *X* rays	1.2 ± 0.3	Gragtmans et al. (1984)
Leukemia in CBA/H mice	HTO and chronic *X* rays	1.2 ± 0.3	Myers and Johnson (1991)
Tumors in C57B1/6N × C3H/He mice	HTO and acute gamma rays	~1[b]	Yokoro et al. (1989)
Transformation in hamster cells *in vitro*	HTO and acute *X* rays	~1	Suzuki et al. (1989)
Transformation in mouse cells *in vitro*	HTO and acute *X* rays	1-2	Little (1986)
Transformation in 10T½ cells	HTO and subacute gamma rays	1.4-1.8	Yamaguchi et al. (1985)

[a]See Table 1 of Straume and Carsten (1993).
[b]Authors did not provide a value of RBE but state that HTO was not very different from gamma rays.

Table 11. Estimates of RBE of tritium beta particles for genetic endpoints[a]

Effect	Radiation and conditions	RBE	Reference
6-Thioguanine resistance in mouse cells *in vitro*	HTO and chronic gamma rays	2.9	Ueno et al. (1989)
6-Thioguanine resistance in mouse cells *in vitro*	^{3}H-amino acid and chronic gamma rays	2.6	Ueno et al. (1989)
6-Thioguanine resistance in mouse cells *in vitro*	Tritiated thymidine (^{3}H-Tdr)[b] and chronic gamma rays	5.9	Ueno et al. (1989)
6-Thioguanine resistance in mouse cells *in vitro*	HTO and gamma rays at 10^{-5} mutant frequency		Nakamura et al. (1985)
	acute	1.5	
	chronic	2.4	
Chromosome aberrations in human sperm *in vitro*	HTO and chronic *X* rays	3	Kamiguchi et al. (1990)
Chromosome aberrations in fish lymphocytes *in vitro*	HTO and chronic gamma rays	1.9	Suyama and Etoh (1985)
Chromosome aberrations in mouse zygotes	HTO and chronic gamma rays	1.8	Matsuda et al. (1985)
Chromosome aberrations in CBA/H mice			Chopra and Heddle (1988)
lymphocytes	HTO and *X* rays	1.1	
spermatogonia	HTO and *X* rays	1.2	
Micronuclei in mammalian cells	HTO and chronic gamma rays	2.0 2.7	Ueno et al. (1982) Kashima et al. (1985)
Mutations in *Drosophila* spermatozoa	HTO and gamma rays	2.7	Byrne and Lee (1989)
Mutations in mice *in vivo*	HTO and chronic gamma rays	2.7	Nomura and Yamamoto (1989)

Table is continued on following page.

Table 11. (continued)

Effect	Radiation and conditions	RBE	Reference
Dominant lethals in male mice	HTO and chronic gamma rays	2.5	Searle (1984)
		1-2	Carsten and Commerford (1976)
Dominant lethals in female mice	HTO and chronic gamma rays	2.5	Xiang-yan et al. (1986)
Specific locus mutations in male mice	HTO and chronic gamma rays	2.0	UNSCEAR (1982)
Dominant lethals in male mice	HTO and chronic gamma rays	2.5	Searle (1984)
		1-2	Carsten and Commerford (1976)

[a]See Table 2 of Straume and Carsten (1993).
[b]Use of methyl-^{3}H-Tdr resulted in identical RBEs.

Table 12. Estimates of RBE for ^{3}H beta particles for chromosome aberrations in human lymphocytes[a]

Radiation and conditions	RBE	Reference
HTO and acute *X* rays	1.9 ± 0.7	Bocian et al. (1977), as refit by Prosser et al. (1983)
HTO and subacute gamma rays	1.49 ± 0.21	Morimoto et al. (1989)
HTO and acute *X* rays	1.13 ± 0.18	Prosser et al. (1983)
HTO and acute gamma rays	3.4 ± 0.6	Prosser et al. (1983) and Lloyd et al. (1975)
HTO and subacute *X* rays	2.6	Vulpis (1984)
HTO and low dose *X* rays	2.0	Estimated from Prosser et al. (1983) and Lloyd et al. (1988)

[a]See Table 3 of Straume and Carsten (1993).

Table 13. Estimates of RBE for ^{3}H beta particles for developmental and related effects[a]

Effect	Radiation and conditions	RBE	Reference
Mouse embryo, two-cell to blastocyte *in vitro*	HTO and chronic gamma rays	1.7	Yamada et al. (1982)
Teratogenic effects in rat embryos	HTO and chronic gamma rays	2.6	Satow et al. (1989)
Cell killing *in vitro*	HTO and chronic gamma rays	1.3	Ueno et al. (1989)
	^{3}H-amino acids and chronic gamma rays	1.7	
	Tritiated thymidine (^{3}H-Tdr)[b] and chronic gamma rays	3.5	

[a]See Table 4 of Straume and Carsten (1993).
[b]Use of methyl-^{3}H-Tdr resulted in identical RBEs.

Table 14. Summary of probability distributions of RBE factors to be used in estimating probability of causation of cancers from exposure to various radiation types.

Radiation type	Exposure	Description	2.5th	50th	97.5th
RBE factors to be used with risks per unit dose at high doses and high dose rates of gamma radiation that are adjusted to low doses and dose rates by use of $DDREF_\gamma$					
Exposure information		**Probability distribution of RBE factor**	**95% confidence interval[a]**		
Photons	Any[b]				
E > 250 keV		Single-valued	—	1.0	—
E = 30-250 keV		Hybrid ($\overline{RBE}_{\gamma,M}$)[c]	1.0	1.9	4.7
E < 30 keV		$\overline{RBE}_{\gamma,M} \times AF_\gamma$	1.1	2.4	6.1
Electrons	Any[b]				
E > 60 keV		Single-valued	—	1.0	—
E = 15-60 keV		Same as 30-250 keV photons	1.0	1.9	4.7
E < 15 keV[d]		Lognormal	1.2	2.7	6.0
Neutrons		Not applicable			
Alpha particles[e]	Chronic[f]	Stepwise-uniform[g] × EF_α	3.0	26	86
RBE factors to be used with risks per unit dose at high doses and high dose rates of gamma radiation, without adjustment to low doses and dose rates by use of $DDREF_\gamma$					
Electrons		Not applicable			
Photons		Not applicable			
Neutrons					
E = 0.1-2 MeV[h]	Acute	Lognormal ($\overline{RBE}_{n,H}$)	1.5	6.7	30
	Chronic	$\overline{RBE}_{n,H} \times EF_n$	1.8	8.9	47
E = 10-100 keV;	Acute	$\overline{RBE}_{n,H}/AF_2$	0.6	3.4	17
E = 2-20 MeV	Chronic	$\overline{RBE}_{n,H} \times EF_n/AF_2$	0.8	4.4	27
E < 10 keV;	Acute	$\overline{RBE}_{n,H}/AF_4$	0.3	1.7	8.7
E > 20 MeV	Chronic	$\overline{RBE}_{n,H} \times EF_n/AF_4$	0.4	2.2	13
Alpha particles		Not applicable			

See following page for footnotes and legend.

Footnotes for Table 14

[a]Lower tails of probability distributions of RBE factors for photons, electrons, and neutrons should be truncated at 1.0; probability distribution for alpha particles has lower bound of 1.0.

[b]For acute exposure to photons or electrons, estimated risks are adjusted by dose and dose-rate effectiveness factor, $DDREF_\gamma$, that depends on the dose received. For acute doses greater than 0.2 Gy, $DDREF_\gamma = 1.0$. For acute doses less than 0.2 Gy, a $DDREF_\gamma$ that can exceed 1.0 is applied; the distribution of possible values approaches $DDREF_\gamma$ for chronic exposure as the dose approaches zero.

[c]Probability distribution assigns weight of 0.25 to value of 1.0 and weight of 0.75 to lognormal distribution having 95% confidence limit between 1.0 and 5.0.

[d]Energy range includes beta particles emitted in decay of ^3H and low-energy Auger electrons; RBE factor does not apply to Auger-emitting radionuclides that are known to be incorporated into DNA.

[e]RBE factor is not applied to inhalation of radon and its short-lived decay products.

[f]Acute exposures to alpha particles emitted by radionuclides generally should not occur.

[g]Probability distribution has 15% of values in range of 1.0-10, 25% in range of 10-20, 30% in range of 20-30, 20% in range of 30-40, 7.5% in range of 40-60, and 2.5% in range of 60-100.

[h]RBE factors for this energy range apply to fission neutrons.

Legend for Table 14

$\overline{RBE}_M$	RBE factor at low doses and low dose rates of reference high-energy gamma radiation.
$\overline{RBE}_H$	RBE factor at high acute doses of reference high-energy gamma radiation; probability distribution is applied at any dose and dose rate of neutrons.
AF_γ	Increase in biological effectiveness, relative to photons of energy 30-250 keV, for photons of energy <30 keV; probability distribution is triangular (minimum of 1.0, mode of 1.3, and maximum of 1.6).
EF_α	Factor representing inverse dose-rate effect for chronic exposure to alpha particles; probability distribution is discrete (70% at 1.0, 20% at 1.5, 7.5% at 2.0, and 2.5% at 3.0).
EF_n	Factor representing inverse dose-rate effect for chronic exposure to neutrons; probability distribution is discrete (50% at 1.0, 30% at 1.5, 15% at 2.0, and 5% at 3.0).
AF_2	Reduction in biological effectiveness, relative to fission neutrons, for neutrons of energy 10-100 keV or 2-20 MeV; probability distribution is lognormal (95% confidence interval between 1.0 and 4.0).
AF_4	Reduction in biological effectiveness, relative to fission neutrons, for neutrons of energy <10 keV or >20 MeV; probability distribution is lognormal (95% confidence interval between 2.0 and 8.0).
$DDREF_\gamma$	Dose and dose-rate effectiveness factor used to adjust risk estimates that apply at high doses and high dose rates of high-energy gamma radiation to exposures at low doses and low dose rates of low-LET radiations.

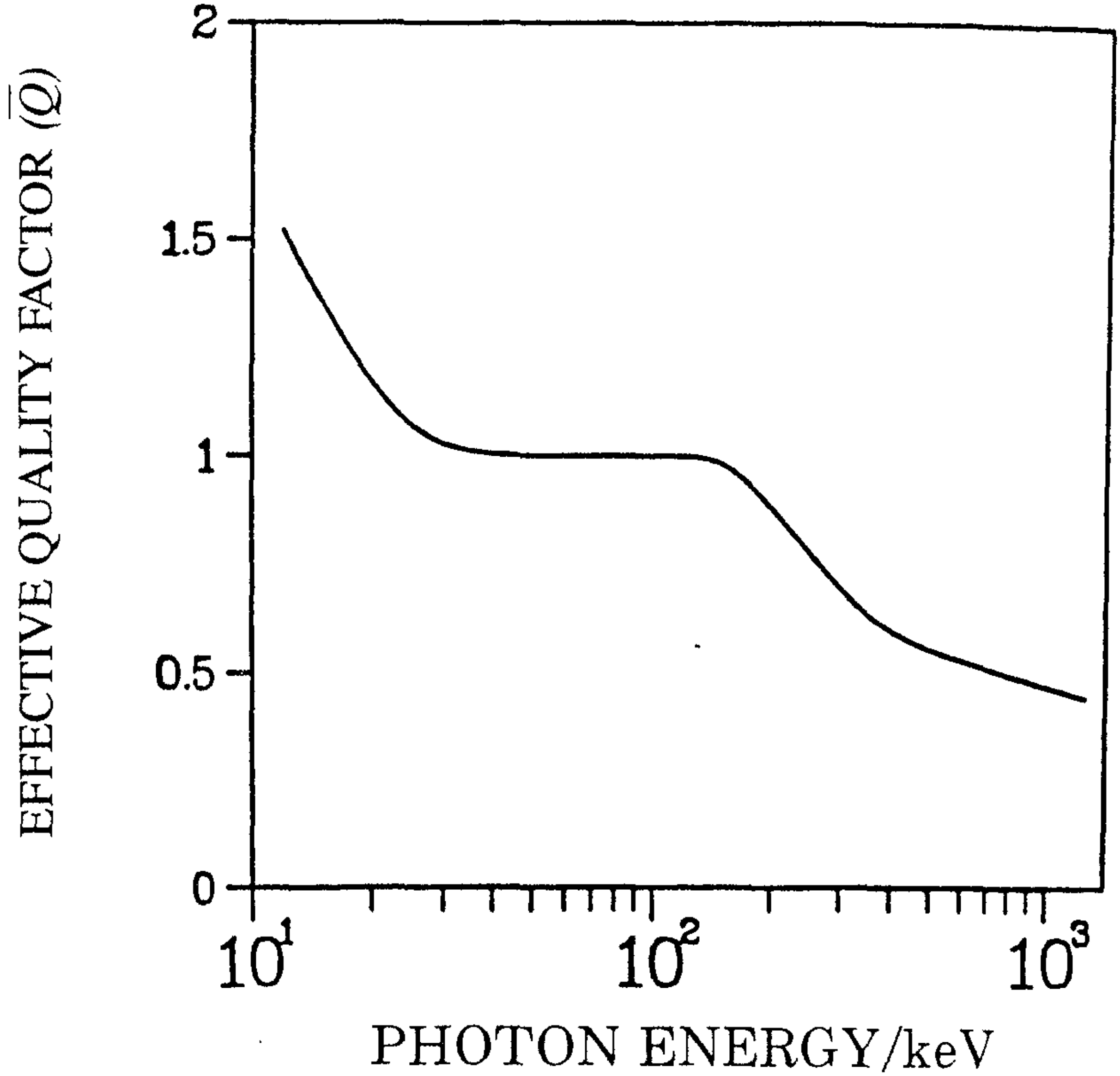

Fig. 1. Calculated values of effective quality factor, $\overline{Q}$, vs. photon energy under conditions of charged-particle equilibrium given in Fig. 3 of ICRU (1986). Quality factor is normalized to unity at energies of orthovoltage X rays often used in radiobiological studies; value for gamma rays emitted in ^{60}Co decay is at right end of curve.

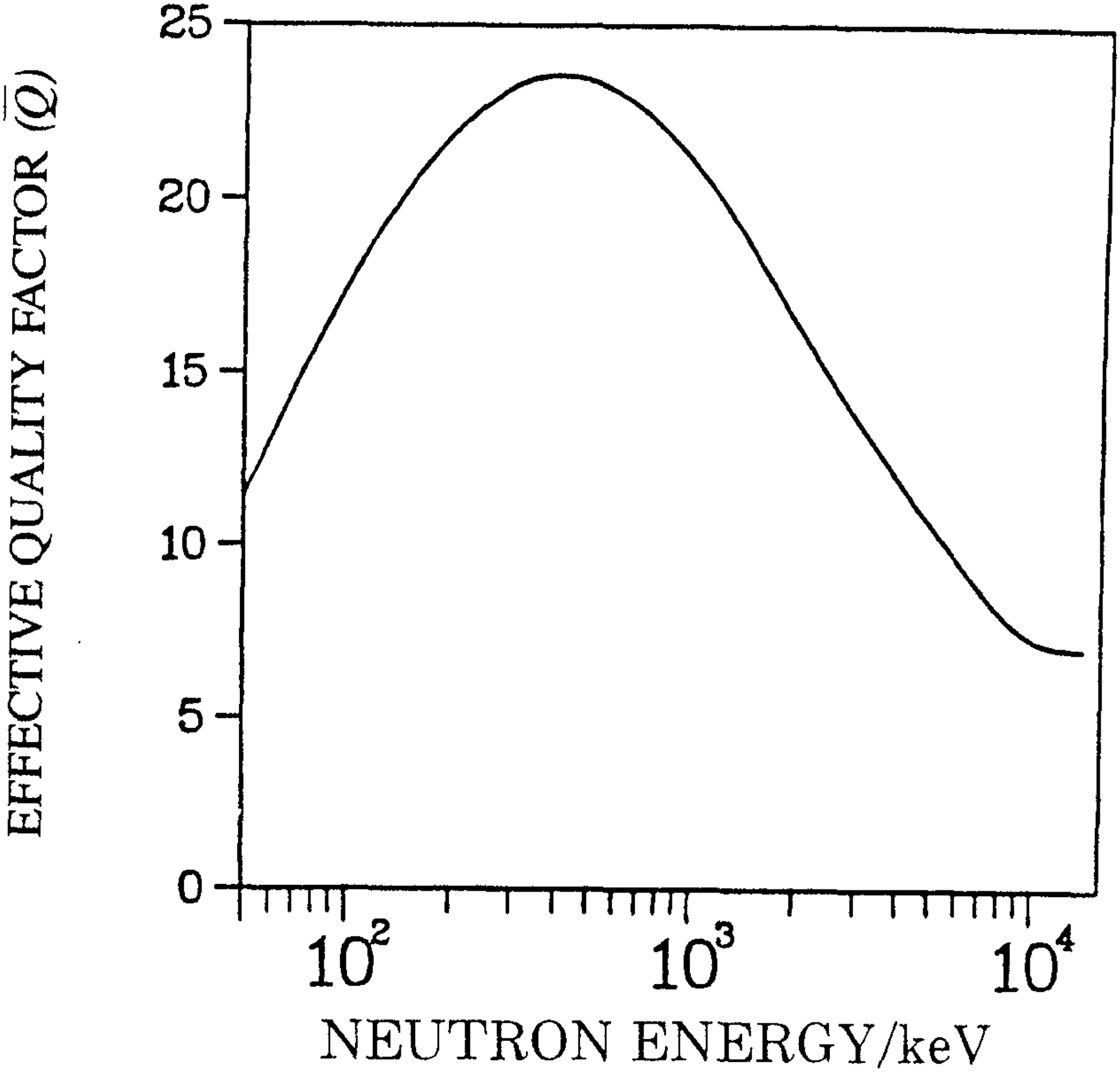

Fig. 2. Calculated values of effective quality factor, $\overline{Q}$, vs. neutron energy under conditions of charged-particle equilibrium given in Fig. 4 of ICRU (1986).

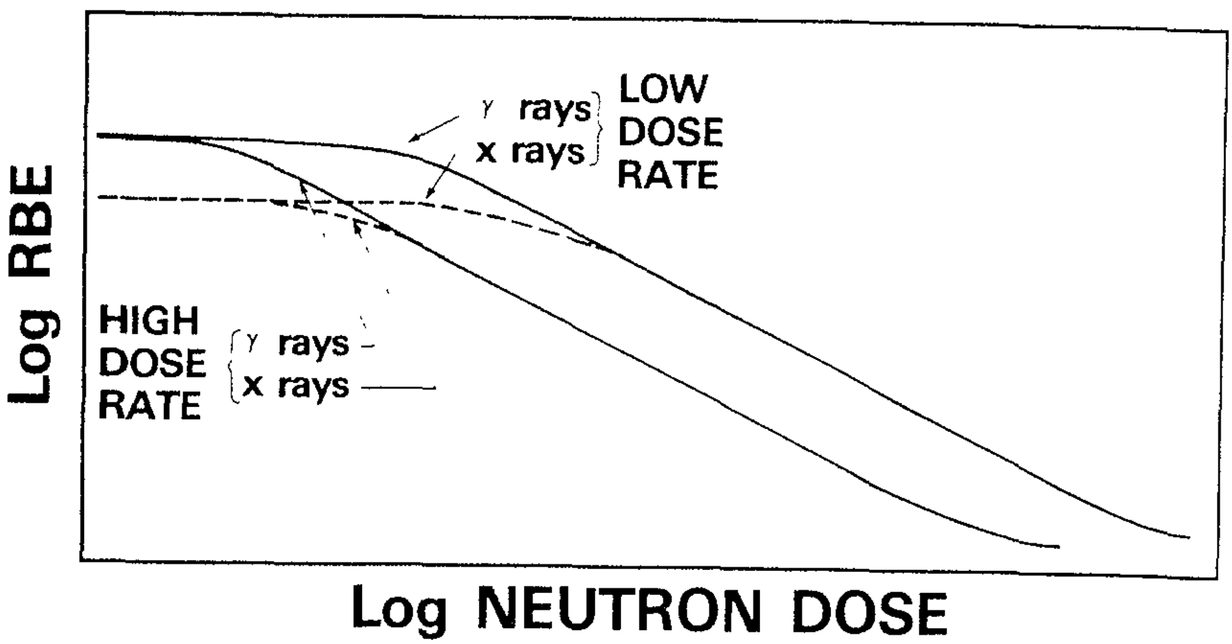

Fig. 3. Schematic representation of increase in RBE for fission neutrons with decreasing dose given in Fig. C-2 of ICRU (1986). Maximum values at low doses are values of RBE_M.

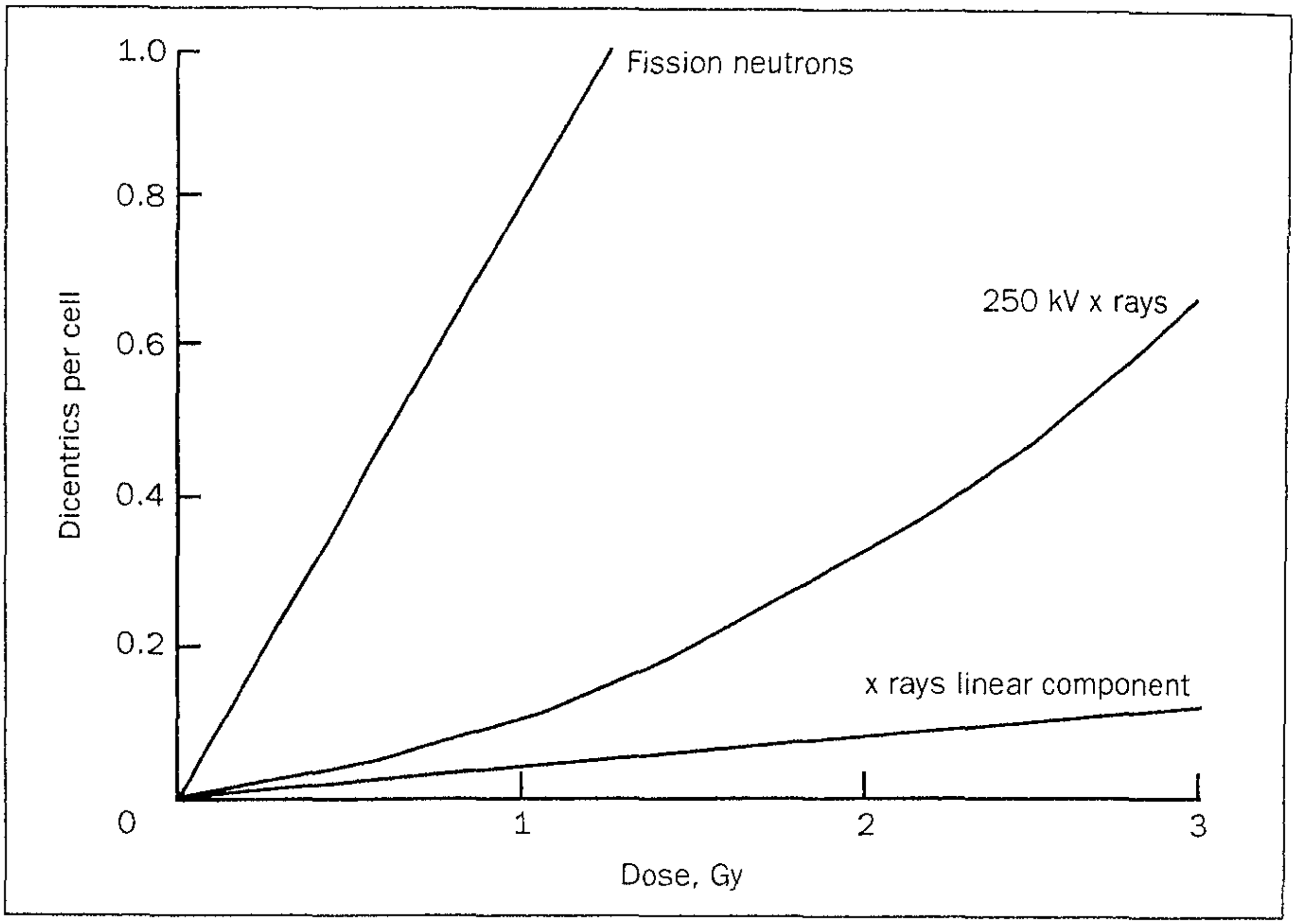

Fig. 4. Representation of linear and linear-quadratic dose-response relationships for fission neutrons and *X* rays, respectively, in studies of induction of dicentric chromosomes in human lymphocytes given in Fig. 1 of Edwards (1997). Separation of two curves at different levels of response illustrates dependence of neutron RBE on dose, as shown in Fig. 3; RBE at low doses and low dose rates, RBE_M, is determined by separation of neutron curve and linear component of *X* ray curve.

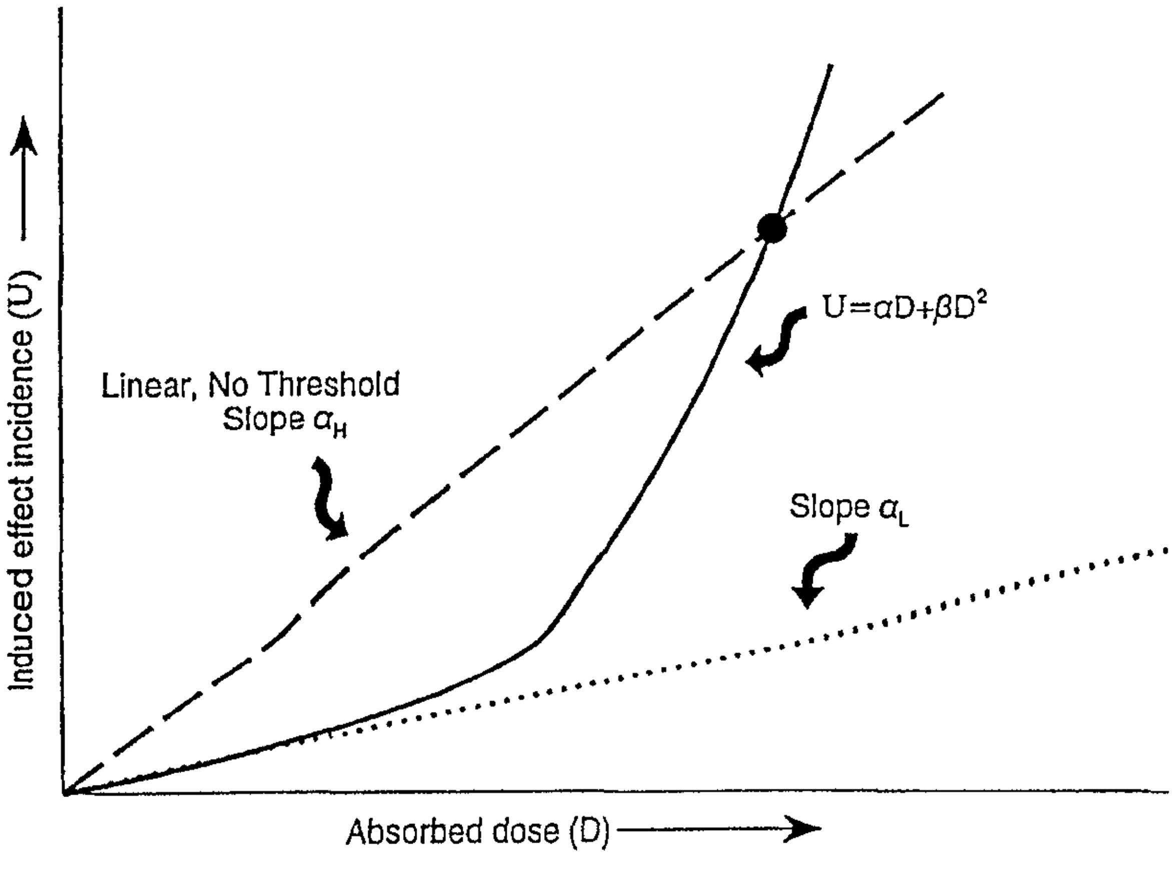

Fig. 5. Representation of linear-quadratic dose-response relationship for low-LET radiations given in Fig. 2 of CIRRPC (1995). Dose and dose-rate effectiveness factor (DDREF) is ratio of linear extrapolation at high doses, α_H, to slope of dose-response curve at low doses, α_L, and, thus, is a function of dose given by $1 + (\beta/\alpha)D$.

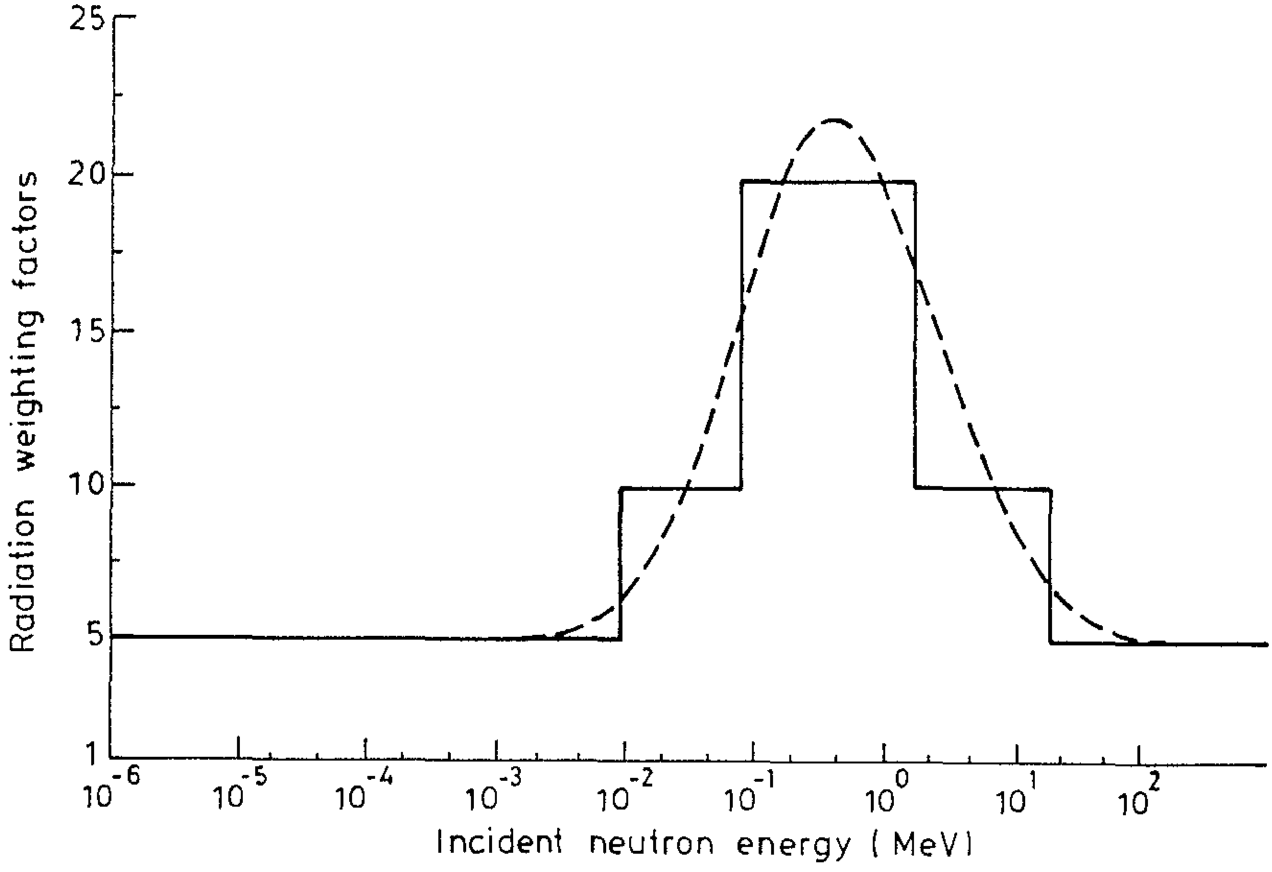

Fig. 6. Radiation weighting factor, w_R, vs. neutron energy currently recommended by ICRP (1991) and NCRP (1993) and given in Fig. A.1 of ICRP (1991). Dashed curve is an approximate given by eq. (4).

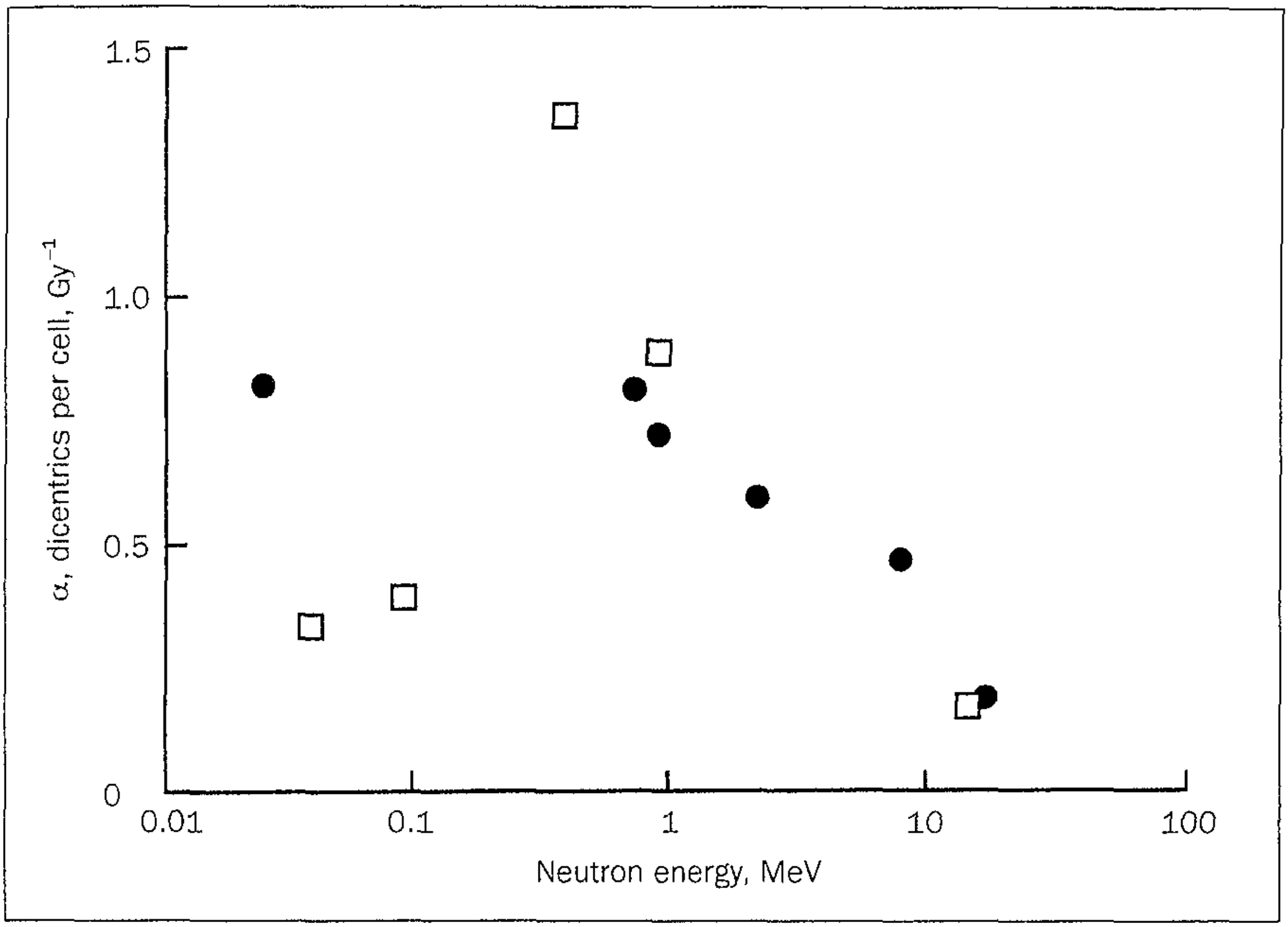

Fig. 7. Variation of RBE_M with neutron energy for induction of dicentric chromosomes in human lymphocytes shown in Fig. 6 of Edwards (1997; 1999). Solid circles are data of Edwards et al. (1985; 1990), and open squares are data of Sevan'kaev et al. (1979).

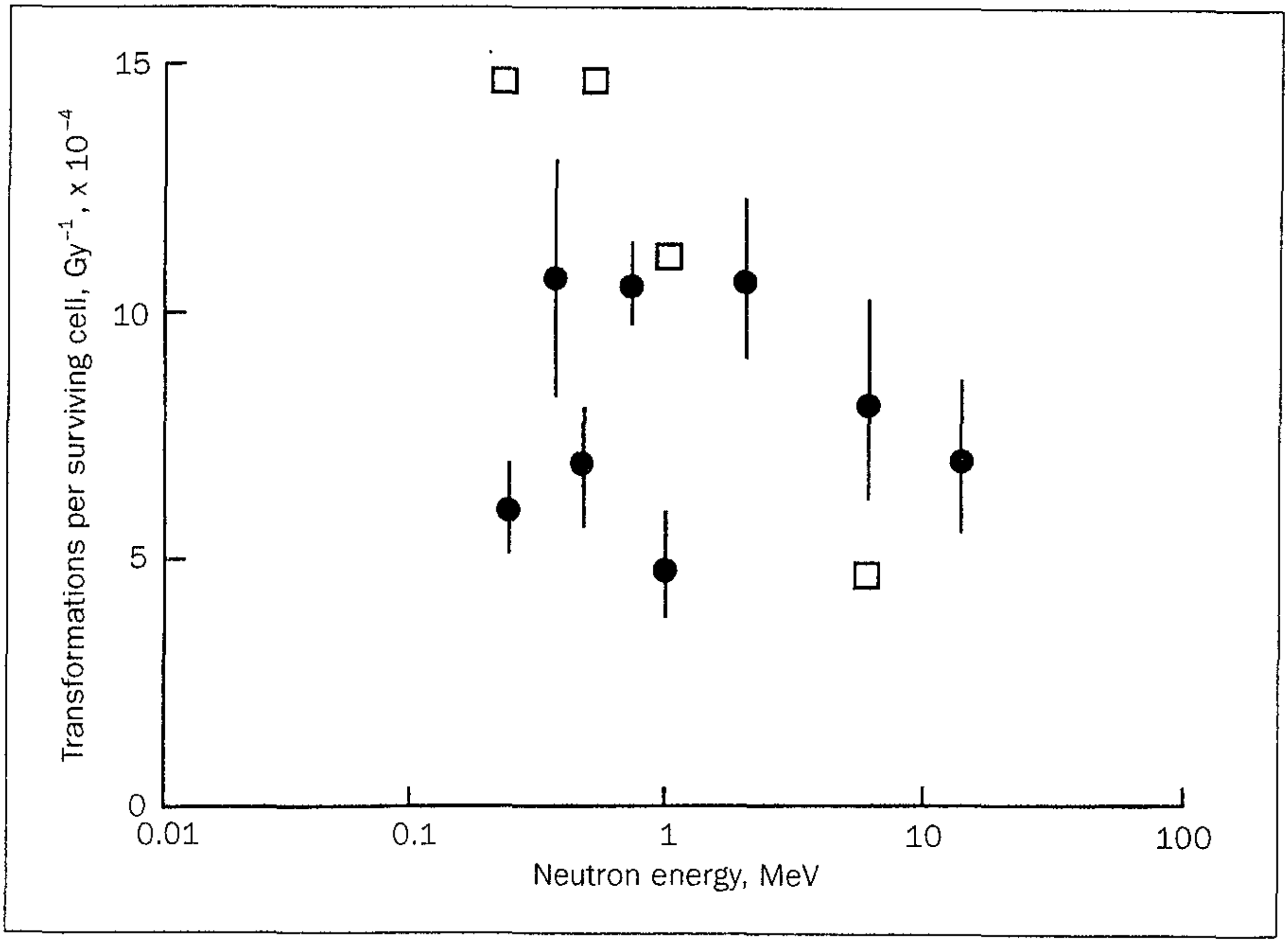

Fig. 8. Variation of RBE_M with neutron energy for transformation of C3H10T½ mouse cells shown in Fig. 7 of Edwards (1997). Solid circles are data of Miller et al. (1989), and open squares are data of Coppola (1993); error bars represent one standard error.

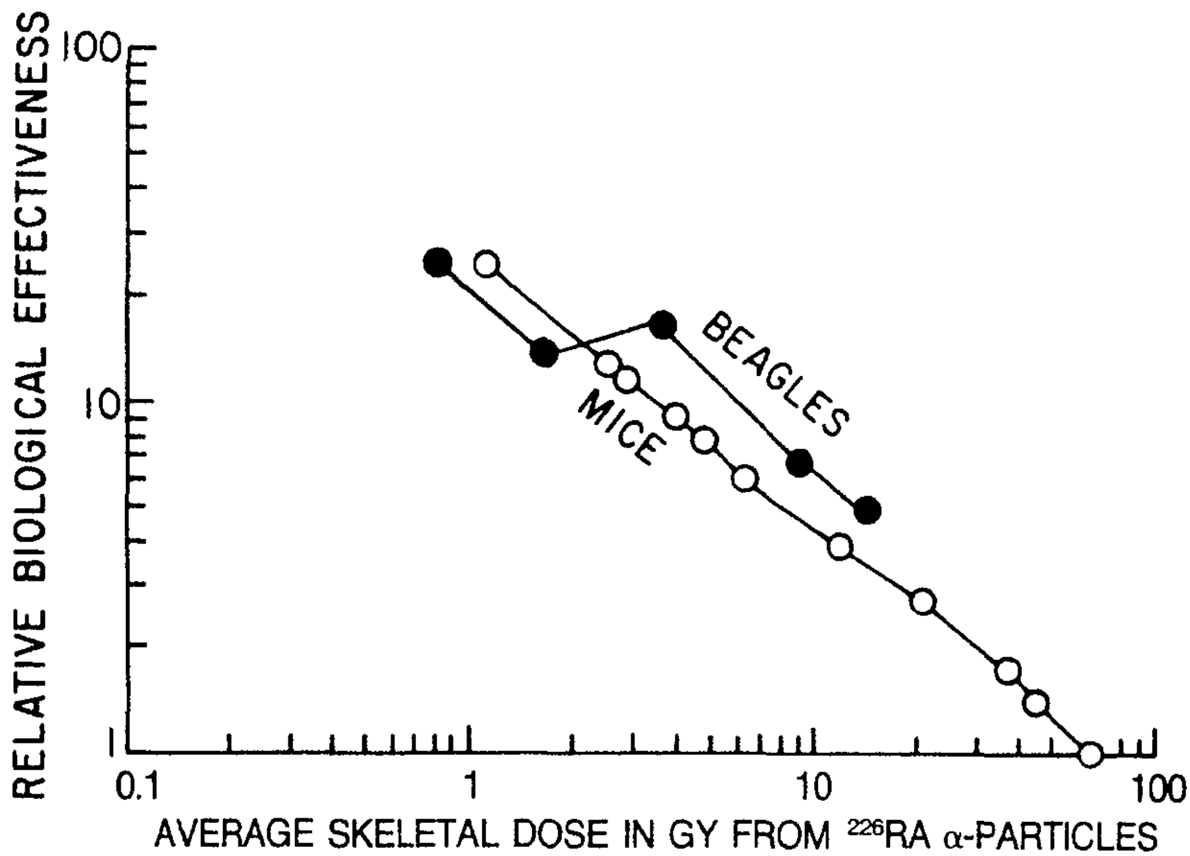

Fig. 9. Biological effectiveness of alpha particles emitted by ^{226}Ra and its decay products, relative to beta particles emitted by ^{90}Sr and ^{90}Y, for induction of bone tumors in mammals given in Fig. 7.3 of NCRP (1990); curves show pronounced dependence of RBE on dose.

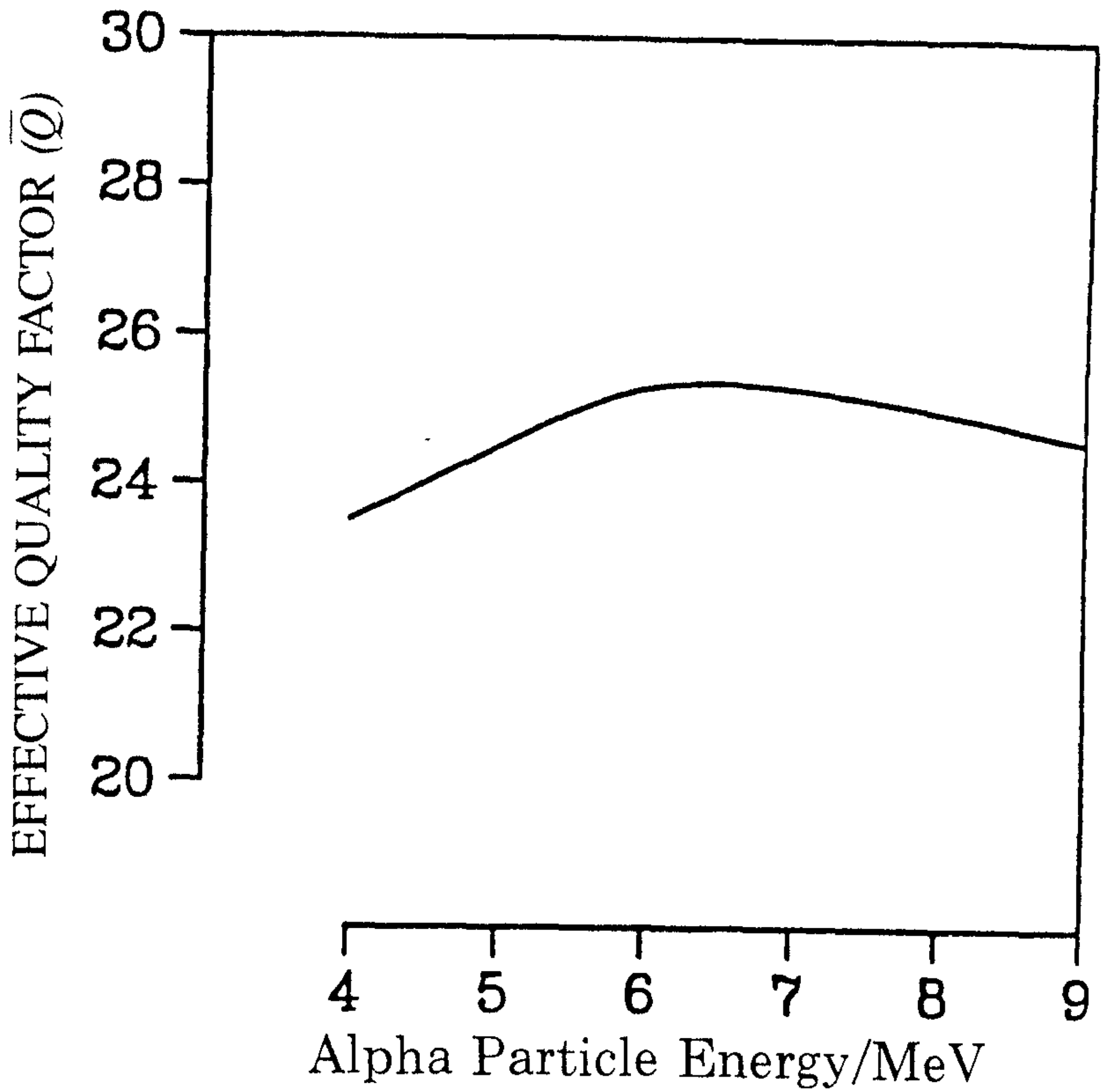

Fig. 10. Calculated values of effective quality factor, $\overline{Q}$, vs. alpha particle energy given in Fig. 5 of ICRU (1986). Values apply to entire range of alpha particles of given initial energy.

REFERENCES

Bauchinger, M., 1984. "Cytogenetic Effects in Human Lymphocytes As a Dosimetry System," p. 15 in *Biological Dosimetry*, ed. by W.G. Eisert and M.L. Mendelsohn, Springer-Verlag, Berlin, Germany.

Bocian, E., Ziembia-Zak, E.B., Rosiek, O., and Sablinski, J., 1977. "Chromosome Aberration in Human Lymphocytes Exposed to Tritiated Water *in Vitro*," *Curr. Topics Radiat. Res. Q.* 12, 168-181.

Boecker, B.B., Hahn, F.F., Muggenburg, B.A., Guilmette, R.A., Griffith, W.C., and McClellan, R.O., 1988. "The Relative Effectiveness of Inhaled Alpha and Beta Emitting Radionuclides in Producing Lung Cancer," p. 1059 in *Radiation Protection Practice, Proceedings of the Seventh International Congress of IRPA*, Vol. II, Pergamon Press, Sydney, Australia.

Brenner, D.J., 1990. "The Microdosimetry of Radon Daughters and Its Significance," *Radiat. Prot. Dosim.* 31, 399-403.

Brenner, D.J., 1999. "Does Fractionation Decrease the Risk of Breast Cancer Induced by Low-LET Radiation?," *Radiat. Res.* 151, 225-229.

Brenner, D.J., and Amols, H.I., 1989. "Enhanced Risk from Low-Energy Screen-Film Mammography X Rays," *Brit. J. Radiol.* 62, 910-914.

Brewen, J.G., and Luippold, H.E., 1971. "Radiation-Induced Human Chromosome Aberrations: *In Vitro* Dose Rate Studies," *Mutat. Res.* 12, 305.

Brewen, J.G., Preston, R.L., and Littlefield, L.G., 1972. "Radiation Induced Human Chromosome Aberrations. III. Aberration Yields Following an Accidental Whole-Body Exposure to ^{60}Co γ-Rays," *Radiat. Res.* 49, 647.

Broerse, J.J., van Bekkum, D.W., Zoetelief, J., and Zurcher, C., 1991. "Relative Biological Effectiveness for Neutron Carcinogenesis in Monkeys and Rats," *Radiat. Res.* 128, S128-S135.

Brooks, A.L., 1975. "Chromosome Damage in Liver Cells from Low Dose Rate Alpha, Beta, and Gamma Irradiation: Derivation of RBE," *Science* 190, 1090.

Brooks, A.L., Mewhinney, J.A., and McClellan, R.O., 1972. "The *in Vivo* Cytogenetic Effects of ^{252}Cf on Liver and Bone Marrow of the Chinese Hamster," *Health Phys.* 22, 701-706.

Byrne, B.J., and Lee, W.R., 1989. "Relative Biological Effectiveness of Tritiated Water to Gamma Radiation for Germ Line Mutations," *Radiat. Res.* 117, 469-479.

Carnes, B.A., Grahn, D., and Thompson, J.F., 1989. "Dose Response Modeling of the Life Shortening in a Retrospective Analysis of the Combined Data from the JANUS Program at Argonne National Laboratory," *Radiat. Res.* 119, 39-56.

Carsten, A.L., and Commerford, S.L., 1976. "Dominant Lethal Mutations in Mice Resulting from Chronic Tritiated Water (HTO) Ingestion," *Radiat. Res.* 66, 609-614.

Chopra, C., and Heddle, J.A., 1988. *Cytogenetic Measurements of the Relative Biological Effectiveness of Tritium*, INFO-0287, Atomic Energy Control Board, Ottawa, Ontario, Canada.

CIRRPC (Committee on Interagency Radiation Research and Policy Coordination), 1995. *Neutron Quality Factor*, ORAU 95/F-29, CIRRPC, Washington, DC.

Coggle, J.E., 1988. "Lung Tumour Induction in Mice after X-Rays and Neutrons," *Int. J. Radiat. Biol.* 53, 585-598.

Coppola, M., 1993. "Specification of Fast Neutron Radiation Quality from Cell Transformation Data," *Radiat. Prot. Dosim.* 46, 211-212.

Cox, R., and Masson, W.K., 1979. "Mutation and Activation of Cultured Mammalian Cells Exposed to Beams of Accelerated Heavy Ions. III. Human Diploid Fibroplasts," *Int. J. Radiat. Biol.* 36, 149-160.

Cox, R., Thacker J., Goodhead, D.T., and Munson, R.J., 1977. "Mutation and Inactivation of Mammalian Cells by Various Ionizing Radiations," *Nature* 267, 425.

Dobson, R.L., Straume, T., Carrano, A.V., Minkler, J.L., Deaven, L.L., Littlefield, L.G., and Awa, A.A., 1991. "Biological Effectiveness of Neutrons from Hiroshima Bomb Replica: Results of a Collaborative Cytogenetic Study," *Radiat. Res.* 142-149.

DOE (U.S. Department of Energy), 1993. "10 CFR Part 835—Occupational Radiation Protection," Final Rule, *Fed. Registr.* 58, 65458-65512; see also Title 10 of *Code of Federal Regulations*, which is published annually by U.S. Government Printing Office, Washington, DC.

Eckerman, K.F., Leggett, R.W., Nelson, C.B., Puskin, J.S., and Richardson, A.C.B., 1999. *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, Federal Guidance Report No. 13, EPA 402-R-99-001, U.S. Environmental Protection Agency, Washington, DC.

Edwards, A.A., 1997. "Relative Biological Effectiveness of Neutrons for Stochastic Effects," *Documents of the NRPB* 8, No. 2, National Radiological Protection Board, Chilton, U.K.

Edwards, A.A., 1999. "Neutron RBE Values and Their Relationship to Judgements in Radiological Protection," *J. Radiol. Prot.* 19, 93-105.

Edwards, A.A., Lloyd, D.C., and Prosser, J.S., 1985. "The Induction of Chromosomal Aberrations in Human Lymphocytes by Accelerated Charged Particles," *Radiat. Prot. Dosim.* 13, 205-209.

Edwards, A.A., Lloyd, D.C., and Prosser, J.S., 1990. "The Induction of Chromosomal Aberrations in Human Lymphocytes by 24 keV Neutrons," *Radiat. Prot. Dosim.* 31, 265-268.

Edwards, A.A., Purrott, R.J., Prosser, J.S., and Lloyd, D.C., 1980. "The Induction of Chromosome Aberrations in Human Lymphocytes by Alpha-Radiation," *Int. J. Radiat. Biol.* 38, 83-91.

EPA (U.S. Environmental Protection Agency), 1994. *Estimating Radiogenic Cancer Risks*, EPA 402-R-93-076, EPA, Washington, DC.

Fabry, L., Leonard, A., and Wambersie, A., 1985. "Induction of Chromosome Aberrations in G_0 Human Lymphocytes by Low Doses of Ionizing Radiations of Different Quality," *Radiat. Res.* 103, 122.

Gragtmans, N.J., Myers, D.K., Johnson, J.R., Jones, A.R., and Johnson, L.D., 1984. "Occurrence of Mammary Tumors in Rats After Exposure to Tritium Beta Rays and 200-kVp X-Rays," *Radiat. Res.* 99, 636-650.

Grahn, D., Lombard, L. S., and Carnes, B. A., 1992. "The Comparative Tumorigenic Effect of Fission Neutrons and Cobalt-60 γ-rays in the B6CF1 Mouse, *Radiat. Res.* 129, 19-36.

Griffith, W.C., Boecker, B.B., Cuddihy, R.G., Guilmette, R.A., Hahn, F.F., McClellan, R.O., Muggenberg, B.A., and Snipes, M.B., 1987. "Preliminary Radiation Risk Estimates of Carcinoma Incidence in the Lung as a Function of Cumulative Radiation Dose Using Proportional Tumor Incidence Rates," p. 196 in *Inhalation Toxicology Research Institute Annual Report*, LMF-120, National Technical Information Service, Springfield, VA.

Griffith, W.C., Boecker, B.B., Gillett, N.A., et al., 1991. "Comparison of Risk Factors for Bone Cancer Induced by Inhaled $^{90}SrCl_2$ and $^{238}PuO_2$," in *Proceedings of EULEP/DOE Joint Bone Radiobiology Workshop*, UDC-472-136, U.S. Department of Energy, Washington, DC.

Hahn, F.F., Griffith, W.C., Boecker, B.B., Muggenberg, B.A., and Lundgren, D.L., 1991. "Comparison of the Effects of Inhaled $^{239}PuO_2$ and β-Emitting Radionuclides on the Incidence of Lung Carcinomas in Laboratory Animals," pp. 916-919 in *Proceedings of IRPA8: Worldwide Achievement in Public and Occupational Health Protection Against Radiation*, 8th International Congress of the International Radiation Protection Association, Vol. I, Pergamon Press, London.

Hei, T.K., Chen, D.J., and Hall, E.J., 1988. "Mutation Induction by Charged Particles of Defined LET," *Carcinogenesis* 9, 1233.

Hunacek, M.M., and Kathren, R.L., 1995. "Alpha Radiation Risk Coefficients for Liver Cancer, Bone Sarcomas, and Leukemia," *Health Phys.* 68, 41-49.

ICRP (International Commission on Radiological Protection), 1979. *Limits for Intakes of Radionuclides by Workers*, ICRP Publication 30, Part 1, *Ann. ICRP* 2, No. 3/4.

ICRP (International Commission on Radiological Protection), 1980. *Biological Effects of Inhaled Radionuclides*, ICRP Publication 31, *Ann. ICRP* 4, No. 1-2.

ICRP (International Commission on Radiological Protection), 1987. *Lung Cancer Risk from Indoor Exposures to Radon Daughters*, ICRP Publication 50, *Ann. ICRP* 17, No. 1.

ICRP (International Commission on Radiological Protection), 1991. *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, *Ann. ICRP* 21, No. 1-3.

ICRP (International Commission on Radiological Protection), 1993. *Protection Against Radon-222 at Home and at Work*, ICRP Publication 65, *Ann. ICRP* 23, No. 2.

ICRP (International Commission on Radiological Protection), 1997. *Conversion Coefficients for Use in Radiological Protection Against External Radiation*, ICRP Publication 74, *Ann. ICRP* 26, No. 3/4.

ICRU (International Commission on Radiation Units and Measurements), 1986. *The Quality Factor in Radiation Protection*, ICRU Report 40, ICRU, Bethesda, MD.

Kamiguchi, M., Tateno, H., and Mikamo, K., 1990. "Dose-Response Relationship for the Induction of Structural Chromosome Aberrations in Human Spermatozoa After *in Vitro* Exposure to Tritium Beta-Rays," *Mutat. Res.* 228, 125-131.

Kashima, M., Joshima, H., and Fukutsu, K., 1985. "Induction of Micronuclei and Some Other Abnormalities in Mouse Bone Marrow Following Tritium Exposure," p. 246-257 in *Proceedings of the Second Workshop on Tritium Radiobiology and Health Physics*, ed. by

H. Matsudaira, T. Yamaguchi, and H. Etoh, NIRS-M-52, National Institute of Radiological Sciences, Chiba, Japan.

Kocher, D.C., 1981. *Radioactive Decay Tables*, DOE/TIC-11026, National Technical Information Service, Springfield, VA.

Land, C., Gilbert, E., and Smith, J., 2002. *Report of the NCI-CDC Working Group to Revise the 1985 NIH Radioepidemiological Tables* (in preparation).

Lee, W., Chiacchierini, R.P., Shleien, B., and Telles, N.C., 1982. "Thyroid Tumors Following ^{131}I or Localized X Irradiation to the Thyroid and Pituitary Glands in Rats," *Radiat. Res.* 92, 307-319.

Little, J.B., 1986. "Induction of Neoplastic Transformation by Low-Dose-Rate Exposure to Tritiated Water," *Radiat. Res.* 107, 225-233.

Littlefield, L.G., Joiner, E.E., and Hubner, K.F., 1989. "Cytogenetic Techniques in Biological Dosimetry: Overview and Example of Dose Estimation in 10 Persons Exposed to Gamma Radiation in the 1984 Mexican ^{60}Co Accident," in *Medical Management of Radiation Accidents*, ed. by F.A. Mettler, Jr., C.A. Kelsey, and R.C. Ricks, CRC Press, Boca Raton, Florida.

Lloyd, D.C., Edwards, A.A., Leonard, A., Deknudt, G., Natarajan, A., Obe, G., Palitti, F., Tanzarella, C., and Tawn, E.J., 1988. "Frequencies of Chromosome Aberrations Induced in Human Blood Lymphocytes by Low Doses of X Rays," *Int. J. Radiat. Biol.* 53, 49-55.

Lloyd, D.C., Edwards, A.A., and Prosser, J.S., 1986. "Chromosome Aberrations Induced in Human Lymphocytes by *in Vitro* Acute X and Gamma Radiation," *Radiat. Prot. Dosim.* 15, 83.

Lloyd, D.C., Purrott, R.J., Dolphin, G.W., Bolton, D., Edwards, A.A., and Corp, M., 1975. "The Relationship Between Chromosome Aberrations and Low-LET Radiation Dose to Human Lymphocytes," *Int. J. Radiat. Biol.* 28, 75-90.

Lubin, J.H., Boice, J.D., Jr., Edling, C., Hornung, R.W., Howe, G., Kunz, E., Kusiak, R.A., Morrison, H.I., Radford, E.P., Samet, J.M., Tirmarche, M., Woodward, A., and Yao, S.X., 1995. "Radon-Exposed Underground Miners and Inverse Dose-Rate (Protraction Enhancement) Effects," *Health Phys.* 69, 494-500.

Mays, C.W., and Finkel, M.P., 1980. "RBE of α-Particles vs. β-Particles in Bone Sarcoma Induction," p. 401 in *Proceedings of the 5th International Congress of IRPA*, Vol. II, Israel Health Physics Society, Jerusalem, Israel.

Matsuda, Y., Yamada, T., and Tobari, I., 1985. "Chromosomal Effects of Tritium in Mouse Zygotes Fertilized *in Vitro*," p. 193-206 in *Proceedings of the Second Workshop on Tritium Radiobiology and Health Physics*, ed. by H. Matsudaira, T. Yamaguchi, and H. Etoh, NIRS-M-52, National Institute of Radiological Sciences, Chiba, Japan.

Miller, R.C., Geard, C.R., Brenner, D.J., Komatsu, K., Marino, S.A., and Hall, E.J., 1989. "Neutron-Energy-Dependent Oncogenic Transformation of C3H10T½ Mouse Cells," *Radiat. Res.* 117, 114-127.

Miller, R.C., Marino, S.A., Napoli, J., Shah, H., Hall, E.J., Geard, C.R., and Brenner, D.J., 2000. "Oncogenic Transformation in C3H10T½ Cells by Low-Energy Neutrons," *Int. J. Radiat. Biol.* 76, 327-333.

Mole, R.H., and Davids, J.A.G., 1982. "Induction of Myeloid Leukaemia and Other Tumours in Mice by Irradiation with Fission Neutrons," pages 31-42 in *Neutron Carcinogenesis*, Commission of the European Communities, Luxembourg.

Mole, R.H., Papworth, D.G., and Corp, M.J., 1983. "The Dose Response X-Ray Induction of Myeloid Leukaemia in Male CBA/H Mice, *Br. J. Cancer* 47, 285-291.

Morimoto, K., Ogawa, Y., Okayama, A., Shirakawa, T., and Miura, K., 1989. "Development of the Monitoring System for Human Exposure to Tritium: Chromosome Aberrations in Human Lymphocytes Exposed to HTO," p. 137-142 in *Tritium Radiobiology and Health Physics*, Proceedings of the Third Japan-U.S. Workshop, ed. by S. Okada, IPPJ-REV-3, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

Muirhead, C.R., Cox, R., Stather, J.W., MacGibbon, B.H., Edwards, A.A., and Haylock, R.G.E., 1993. "Relative Biological Effectiveness," pages 126-139 in *Documents of the NRPB* 4, No. 4, National Radiological Protection Board, Chilton, U.K.

Myers, D.K., and Johnson, J.R., 1991. *Toxicity and Dosimetry of Tritium: A Review*, Atomic Energy Control Board, Ottawa, Ontario, Canada; see also Myers, D.K., and Johnson, J.R., 1990. *RBE of Tritium and Induction of Myeloid Leukemia and CBA/H Mice*, INFO-0360, Atomic Energy Control Board, Ottawa, Ontario, Canada.

Nakamura, N., Morikawa, N., and Okada, S., 1985. "Dose Rate Effects of Mutation Induction by Tritiated Water in Mouse Leukemia Cells," p. 95-100 in *Proceedings of the Second Workshop on Tritium Radiobiology and Health Physics*, ed. by H. Matsudaira, T. Yamaguchi, and H. Etoh, NIRS-M-52, National Institute of Radiological Sciences, Chiba, Japan.

National Research Council, 1988. *Health Risks of Radon and Other Internally Deposited Alpha-Emitters*, BEIR IV, National Academy Press, Washington, DC.

NCRP (National Council on Radiation Protection and Measurements), 1971. *Protection Against Neutron Radiation*, Second Edition, NCRP Report No. 38, NCRP, Bethesda, MD.

NCRP (National Council on Radiation Protection and Measurements), 1985. *A Handbook of Radioactivity Measurements Procedures*, Second Edition, NCRP Report No. 58, NCRP, Bethesda, MD.

NCRP (National Council on Radiation Protection and Measurements), 1990. *The Relative Biological Effectiveness of Radiations of Different Quality*, NCRP Report No. 104, NCRP, Bethesda, MD.

NCRP (National Council on Radiation Protection and Measurements), 1991. *Conceptual Basis for Calculations of Absorbed-Dose Distributions*, NCRP Report No. 108, NCRP, Bethesda, MD.

NCRP (National Council on Radiation Protection and Measurements), 1993. *Limitation of Exposure to Ionizing Radiation*, NCRP Report No. 116, NCRP, Bethesda, MD.

Nomura, T., and Yamamoto, O., 1989. "*In Vivo* Somatic Mutation in Mice Induced by Tritiated Water," p. 230-233 in *Tritium Radiobiology and Health Physics*, Proceedings of the Third Japan-U.S. Workshop, ed. by S. Okada, IPPJ-REV-3, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

NRC (U.S. Nuclear Regulatory Commission), 1991. "10 CFR Part 20 et al.—Standards for Protection Against Radiation," *Fed. Registr.* 56, 23360-23474; see also Title 10 of *Code of Federal Regulations*, which is published annually by U.S. Government Printing Office, Washington, DC.

Pomerantseva, M.D., 1964. "The Genetic Activity of Various Types of Ionizing Radiation," *Radiobiologiya* 4, 13.

Prosser, J.S., Lloyd, D.C., Edwards, A.A., and Stather, J.W., 1983. "The Induction of Chromosome Aberrations in Human Lymphocytes by Exposure to Tritiated Water *in Vitro*," *Radiat. Protect. Dosim.* 4, 21-26.

Purrott, R.J., Edwards, A.A., Lloyd, D.C., and Stather, J.W., 1980. "The Induction of Chromosome Aberrations in Human Lymphocytes by *in Vitro* Irradiation with α-Particles from Plutonium-239," *Int. J. Radiat. Biol.* 38, 277-284.

Ron, E., Lubin, J.H., Shore, R.E., Mabuchi, K., Modan, B., Pottern, L.M., Scheider, A.B., Tucker, M.A., and Boice, J.D., Jr., 1995. "Thyroid Cancer after Exposure to External Radiation: A Pooled Analysis of Seven Studies," *Radiat. Res.* 141, 259-277.

Satow, Y., Lee, J., and Sawada, S., 1989. "Teratogenic Effect of Tritium Water and Tritium Simulator on Rat Embryos," p. 280-286 in *Tritium Radiobiology and Health Physics*, Proceedings of the Third Japan-U.S. Workshop, ed. by S. Okada, IPPJ-REV-3, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

Schmid, E., Regulla, D., Guldbakke, S., Schlegel, D., and Bauchinger, M., 2000. "The Effectiveness of Monoenergetic Neutrons at 565 keV in Producing Dicentric Chromosomes in Human Lymphocytes at Low Doses," *Radiat. Res.* 154, 307-312.

Searle, A.G., 1984. "Genetic Effects of Tritium in Mammals," p. 303-310 in *Proceedings of the European Seminar on the Risks from Tritium Exposure*, EUR 9056 EN, Commission of the European Communities, Mol, Belgium.

Searle, A.G., Beechey, C.V., Green, D., and Humphreys, E.R., 1976. "Cytogenetic Effects of Protracted Exposures to Alpha Particles from ^{239}Pu and to Gamma Rays from ^{60}Co Compared in Male Mice," *Mutat. Res.* 41, 297-310.

Sevan'kaev, A.V., Zherbin, E.A., Luchnik, N.V., Obaturov, G.M., Kozloo, G.M., Tayatte, E.G., and Kapchigasher, S.P., 1979. "Neutron-Induced Cytogenetic Effects in Lymphocytes of Human Peripheral Blood *in Vitro*. I. Dose Dependence of the Effects of Neutrons of Different Energies on Various Types of Chromosome Aberrations," *Genetika* 15, 1046-1060.

Shleien, B., Slaback, L.A., Jr., and Birky, B.K. (eds.), 1998. *Handbook of Health Physics and Radiological Health*, Third Edition, Williams & Wilkins, Baltimore, MD.

Sinclair, W.K., 1985. "Experimental RBE Values of High-LET Radiations at Low Doses and the Implications for Quality Factor Assignment," *Radiat. Prot. Dosim.* 13, 319-326.

Sinclair, W.K., 1996. "The Present System of Quantities and Units for Radiation Protection," *Health Phys.* 70, 781-786.

Stanton, L., Day, J.L., Lightfoot, D.A., Villafana, T., and Rauch, P.L., 1979. "Rapid Computation of Diagnostic X-Ray Bremsstrahlung Spectra," *Radiol.* 130, 477-484.

Storer, J.B., Serrano, L.J., Darden, E.B., Jr., Jernigan, M.C., and Ullrich, R.L., 1979. "Life shortening in RFM and BALB/c Mice as a Function of Radiation Quality, Dose and Dose Rate," *Radiat. Res.* 78, 122-161.

Storer, J.B., and Ullrich, R.L., 1983. "Life Shortening in BALB/c Mice Following Brief, Protracted or Fractionated Exposures to Neutrons," *Radiat. Res.* 96, 335-347.

Straume, T., and Carsten, A.L., 1993. "Tritium Radiobiology and Relative Biological Effectiveness," *Health Phys.* 65, 657-672.

Straume, T., 1995. "High-Energy Gamma Rays in Hiroshima and Nagasaki: Implications for Risk and w_R," *Health Phys.* 69, 954-956.

Suyama, I., and Etoh, H., 1985. "Chromosome Effects of Tritium on Lymphocytes of the Telost, *Umbra Limi*," p. 146-156 in *Proceedings of the Second Workshop on Tritium Radiobiology and Health Physics*, ed. by H. Matsudaira, T. Yamaguchi, and H. Etoh, NIRS-M-52, National Institute of Radiological Sciences, Chiba, Japan.

Suzuki, F., Mori, T., Nikaida, O., Suzuki, K., and Watanabe, M., 1989. "Neoplastic Transformation and Chromosome Aberration Induced by Tritiated Water in Golden Hamster Embryo Cells," p. 211-216 in *Tritium Radiobiology and Health Physics*, Proceedings of the Third Japan-U.S. Workshop, IPPJ-REV-3, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

Thacker, J., Stretch, A., and Stephens, M.A., 1979. "Mutation and Inactivation of Cultured Mammalian Cells Exposed to Beams of Accelerated Heavy Ions. II. Chinese Hamster V79 Cells," *Int. J. Radiat. Biol.* 36, 137-148.

Thomas, B.A., and Hoffman, F.O., 2000. *The Estimate of Excess Lifetime Risk of Cancer Incidence Associated with Discrete Routine Releases of Tritiated Water Vapor (HTO) from the National Tritium Labelling Facility at Lawrence Berkeley National Laboratory*, SOR/TR-003-900, SENES Oak Ridge, Inc., Oak Ridge, TN.

Thompson, D.E., Mabuchi, K., Ron, E., Soda, M., Tokunaga, M., Ochikubo, S., Sugimoto, S., Ikeda, T., Terasaki, M., Izumi, S., and Preston, D.L., 1994. "Cancer Incidence in Atomic Bomb Survivors. Part II: Solid Tumors, 1958-1987," *Radiat. Res.* 137, S17-S67.

Turner, J.E., 1995. *Atoms, Radiation, and Radiation Protection*, Second Edition, John Wiley & Sons, New York.

Ueno, A.M., Furuno-Fukushi, I., and Matsudaira, H., 1982. "Induction of Cell Killing, Micronuclei and Mutation to 6-Thioguanine Resistance After Exposure to Low Dose-Rate Gamma Rays and Tritiated Water in Cultured Mammalian Cells (L5178Y)," *Radiat. Res.* 91, 447-456.

Ueno, A.M., Furuno-Fukushi, I., and Matsudaira, H., 1989. "Cell Killing and Mutation to 6-Thioguanine Resistance After Exposure to Tritiated Amino Acids and Tritiated Thymidine in Cultured Mammalian Cells," p. 200-210 in *Tritium Radiobiology and Health Physics*, Proceedings of the Third Japan-U.S. Workshop, ed. by S. Okada, IPPJ-REV-3, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

Ullrich, R.L., 1980. "Effects of Split Doses of X-Rays or Neutrons on Lung Tumor Formation in RFM Mice," *Radiat. Res.* 83, 138-145.

Ullrich, R.L., 1984. "Tumor Induction in BALB/c Mice after Fractionated or Protracted Exposures to Fission Spectrum Neutrons," *Radiat. Res.* 97, 587-597.

Ullrich, R.L., Jernigan, M.C., Cosgrove, G.E., Satterfield, L.C., Bowles, N.D., and Storer, J.B., 1976. "The Influence of Dose and Dose Rate on the Incidence of Neoplastic Disease in RFM Mice after Neutron Irradiation," *Radiat. Res.* 68, 115-131.

Ullrich, R.L., Jernigan, M.C., and Storer, J.B., 1977. "Neutron Carcinogenesis Dose and Dose-Rate Effects in BALB/c Mice," *Radiat. Res.* 72, 487-498.

Ullrich, R.L., Jernigan, M.C., and Adams, L.M., 1979. "Induction of Lung Tumors in RFM Mice after Localized Exposures to X-Rays or Neutrons," *Radiat. Res.* 80, 464-473.

Ullrich, R.L., and Preston, R.J., 1987. "Myeloid Leukemia in Male RFM Mice Following Irradiation with Fission Spectrum Neutrons or γ-Rays," *Radiat. Res.* 109, 165-170.

Underbrink, A.G., Sparrow, R.C., Sparrow, A.H., and Rossi, H.H., 1970. "RBE of X Rays and 0.43 MeV Monoenergetic Neutrons on Somatic Mutations and Loss of Reproductive Integrity in *Tradescantia* Stamen Hairs," p. 373 in *Symposium on Neutrons in Radiobiology*, CONF-691106, Oak Ridge National Laboratory, Oak Ridge, Tennessee; see also *Radiat. Res.* 44, 187.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 1982. *Ionizing Radiation: Sources and Biological Effects*, Report to the General Assembly, with Annexes, United Nations, New York.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000. "Epidemiological Evaluations of Radiation-Induced Cancer," Annex I in *Sources and Effects of Ionizing Radiation*, Vol. II, pp. 298-450, United Nations, New York.

Upton, A.C., Randolph, M.L., Conklin, J.W., Kastenbaum, M.A., Slater, M., Melville, G.S.J., Conte, F.P., and Sproul, J.A., Jr., 1967. "Late Effects of Fast Neutrons and Gamma Rays in Mice as Influenced by the Dose Rate of Irradiation: Life Shortening," *Radiat. Res.* 32, 493-509.

Upton, A.C., Randolph, M.L., and Conklin, J.W., 1970. "Late Effects of Fast Neutrons and Gamma-Rays in Mice as Influenced by the Dose Rate of Irradiation: Induction of Neoplasia," *Radiat. Res.* 41, 467-491.

Vulpis, N., 1984. "The Induction of Chromosome Aberrations in Human Lymphocytes by *in Vitro* Irradiation with Beta Particles from Tritiated Water," *Radiat. Res.* 97, 511-518.

Wolf, C., Lafuma, J., Masse, R., Morin, M., and Kellerer, A.M., 2000. "Neutron RBE for Induction of Tumors of High Lethality in Sprague-Dawley Rats," *Radiat. Res.* 154, 412-420.

Xiang-yan, Z., Jin-chan, D., Xin-sheng, G., and Lu-xin, W., 1986. "Tritium Beta-Ray and ^{60}Co Gamma-Ray Caused Dominant Lethal Mutation in Mice," *Chinese Med. J.* 99, 420-423.

Yamada, T., Yukawa, O., Asami, K., and Nakazawa, T., 1982. "Effect of Chronic HTO Beta or ^{60}Co Gamma-Radiation on Pre-implantation Mouse Development *in Vitro*," *Radiat. Res.* 93, 359-369.

Yamaguchi, T., Yasukawa, M., Terasima, T., and Matsudaira, H., 1985. "Malignant Cell Transformation Induced by Tritiated Water in Mouse 10T½ Cells," p. 136-145 in *Proceedings of the Second Workshop on Tritium Radiobiology and Health Physics*, ed. by H. Matsudaira, T. Yamaguchi, and H. Etoh, NIRS-M-52, National Institute of Radiological Sciences, Chiba, Japan.

Yokoro, K., Yamamoto, O., Seyama, T., Nitta, Y., and Niwa, O., 1989. "Carcinogenic Effect of Tritiated Water (HTO) in Mice in Comparison with Those of Fission Neutrons and Gamma-Rays," p. 233-238 in *Tritium Radiobiology and Health Physics*, Proceedings of the Third Japan-U.S. Workshop, ed. by S. Okada, IPPJ-REV-3, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.